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INTERLABORATORY MANIKIN TESTING, MATHEMATICAL MODELING, AND HUMAN RESEARCH DATA

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United States Army
Medical Research & Materiel Command

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USARIEM TECHNICAL REPORT T18-03

INTERLABORATORY MANIKIN TESTING, MATHEMATICAL MODELING, AND HUMAN RESEARCH DATA

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14. ABSTRACT
A long-standing and productive partnership between the United States Department of Defense (DOD) and the Department of Defence of Australia (ADOD) has helped enable significant scientific improvements within life sciences. These collaborations span across the full spectrum of life science activities that have direct and indirect benefit to modern military service members. This report highlights a positive example of this partnership, specifically between the US Army Research Institute of Environmental Medicine (USARIEM) and the Defence Science and Technology Group (DST), under a formal Project Arrangement (PA) for Human Thermoregulatory Models for Thermal Safety. This report outlines a combination of human research data, joint analysis for model validation, materiel sharing of three chemical protective ensembles and inter-laboratory thermal manikin testing and data exchange for comparison.

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thermal manikins; biophysics; protective clothing; HSDA; predictive modeling; thermoregulation; heat stress

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EXECUTIVE SUMMARY

A long-standing and productive partnership between the United States Department of Defense (DOD) and the Department of Defence of Australia (ADOD) has helped enable significant scientific improvements within life sciences. These collaborations span across the full spectrum of life science activities that have direct and indirect benefit to modern military service members. This report highlights a positive example of this partnership, specifically between the US Army Research Institute of Environmental Medicine (USARIEM) and the Defence Science and Technology Group (DST), under a formal Project Arrangement (PA) for Human Thermoregulatory Models for Thermal Safety [1].

Included within the objectives of this collaborative partnership between USARIEM and DST are equipment sharing, data exchange, and collaborative work with human research and thermoregulatory models. This report outlines a combination of many of these elements, including sharing of DST human research data, joint analysis for model validation, materiel sharing of three chemical protective ensembles and inter-laboratory thermal manikin testing and data exchange for comparison.

INTRODUCTION

A long-standing and productive partnership between the United States Department of Defense (DOD) and the Department of Defence of Australia (ADOD) has helped enable significant scientific improvements within life sciences. One key area of this collaboration includes the evaluation of clothing and individual equipment (CIE) worn by military service members. The spectrum of CIE scientific evaluations include three main areas: biophysical evaluations, biomedical modeling, and human research studies. This collaborative study has looked to evaluate each of these facets of research and compare the precision of methods between the two organizations.

Biophysical evaluations can be conducted for materials at the swatch level (via sweating guarded hot plate); for component items (e.g., gloves, boots), using thermal manikin components, e.g., head, foot, or hand specific manikins; and whole-system level properties can be tested using full-body thermal manikins. This study has specifically looked at the comparison of whole-body manikin evaluations of chemical, biological, radiological, and nuclear (CBRN) personal protective clothing between two laboratories, the United States Army Research Institute of Environmental Medicine (USARIEM), and the Australia Defense Science and Technology Group (DST).

Modeling using biophysics-based approaches allows for quantitative comparisons of predicted physiological outcomes that are specific to the influence of the clothing properties. These mathematical models are typically binned into three types: rational, empirical, and hybrid. Rational (mechanistic) models are mathematical representations of responses due to principle based sciences (physics, physiology, chemistry). Empirical (functional) models provide the mathematical representation of observed outcomes or relationships of variables based on experimental data. The hybrid approach (most functional physiological models) are a combination of these two approaches. This study has specifically used the comparisons of the Heat Strain Decision Aid (HSDA) [2], a hybrid model, that is mostly empirically-based, to compare human, manikin, and predictive data between the two laboratories.

To demonstrate the precision of the HSDA model, data were collected for three CBRN ensembles using sweating thermal manikins, physiological responses were collected during a controlled human research study, and modeling was used to compare predictions to observed values. This report outlines the findings from this work.

METHODS

This study compared the biophysical testing results of three CBRN ensembles between the two laboratories and then evaluated the accuracy of the HSDA model when compared to human research data.

Clothing Biophysics

The biophysical characteristics, thermal resistance (R_t) and evaporative resistance (R_{et}), of three CBRN ensembles were assessed according to American Society for Testing and Materials (ASTM) standards (ASTM F1291-16 and F2370-16) [3-4]. Measures of R_t were then converted to units of clo, where the total insulation includes clothing and boundary air layers. Measures of R_t and R_{et} were used to calculate the vapor permeability index (i_m), a non-dimensional measure of water vapor resistance of materials. Lastly a ratio of i_m and R_t in clo units (i_m/clo) was used to characterize an ensemble's evaporative potential [5-6].

$$R_t = \frac{(T_s - T_a)}{Q/A}\,[\mathrm{m^2K/W}] \qquad \text{Eq 1.}$$

$$1\ clo = 0.155\ [\mathrm{m^2K/W}] \qquad \text{Eq 2.}$$

$$R_{et} = \frac{(P_{sat} - P_a)}{Q/A}\,[\mathrm{m^2Pa/W}] \qquad \text{Eq 3.}$$

$$i_m = \frac{60.6515 \cdot R_t}{R_{et}} \qquad \text{Eq 4.}$$

where T_s is surface temperature, T_a is the air temperature in °C or K; Q is power input in W to maintain T_s at a given set point; A is the surface area of the manikin in m^2. P_{sat} is vapor pressure in Pascal at the surface of the manikin (assuming full saturation), and P_a is vapor pressure, in Pascal, of the chamber environment.

Ensembles were tested using two sweating thermal manikins, Newton 20 zone and Newton 26 zone (Thermetrics, Seattle, WA http://www.thermetrics.com/) (Figure 1), located in two separate environmentally controlled climate chambers at the US Army Research Institute of Environmental Medicine (USARIEM) (Newton 20 zone) and the Defence Science & Technology Group (DST) (Newton 26 zone).

Wind Velocity Coefficient Assessments

Standard chamber test conditions were maintained during testing in accordance with ASTM standards (Table 1); while additional testing was conducted at higher wind velocity conditions to determine biophysical changes as a result of increased wind velocity. The target wind velocities for testing included near still air (0.4 m/s ASTM standard), 1.12, and 2.2 m/s; however, as maintaining these conditions is relatively difficult, fan power settings (20, 50, and 80%) were used to approximate these speeds and measures were obtained of actual values. These additional test conditions were used to establish wind velocity coefficient values, specific to each ensemble for modeling purposes [7]. In order to compare each measured value, given differing wind velocities, statistical regression trend lines were added to each and compared as a group to the other (i.e., USARIEM tests vs. DST tests).

Figure 1. Newton 20 and 26 zone sweating thermal manikin

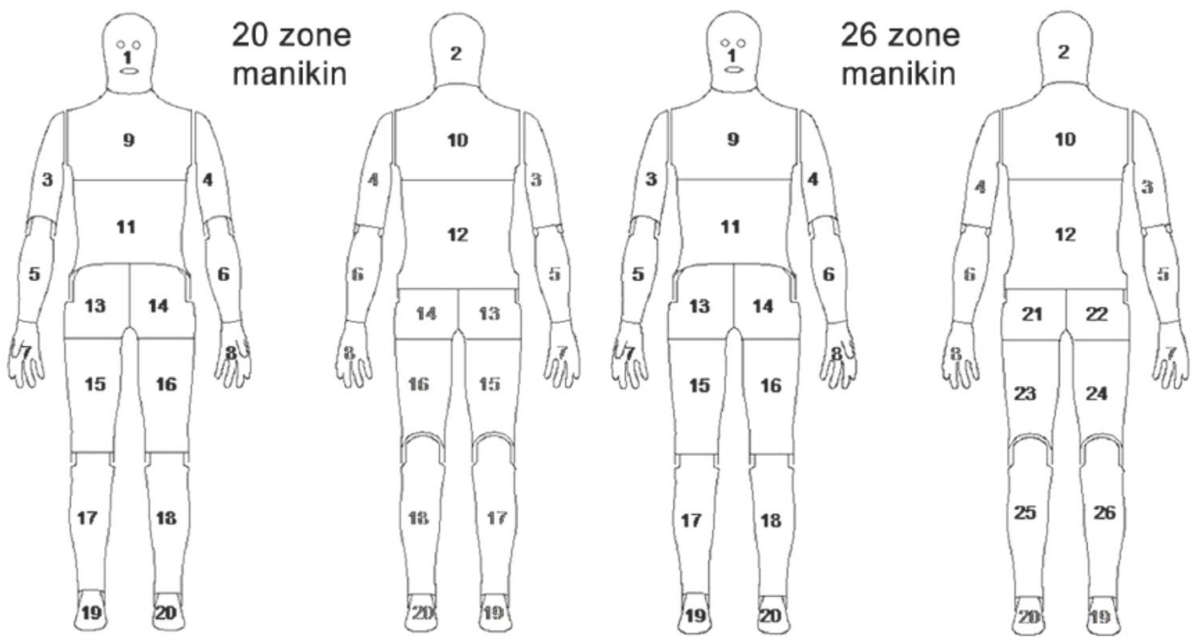


Table 1. American Society for Testing and Materials (ASTM) chamber and manikin conditions and additional conditions for thermal *(R_t)* and evaporative (R_{et}) resistance

Test	Variable (unit)	Skin / surface temperature (T_s, °C)	Ambient temperature (T_a, °C)	Relative humidity (RH, %)	Goal Wind velocity (V, ms^{-1})	Skin Saturation (%)
Test 1	R_t (m^2K/W)	35	20	50	0.40	0
Test 2		35	20	50	1.12	0
Test 3		35	20	50	2.20	0
Test 4	R_{et} (m^2Pa/W)	35	35	40	0.40	100
Test 5		35	35	40	1.12	100
Test 6		35	35	40	2.20	100

Ensembles

Three configurations of Chemical, Biological, Radiological, and Nuclear (CBRN) personal protective equipment (PPE) were assessed (Table 2).

Table 2. Clothing Configurations Tested

Label	Ensemble	Weight	Description
Ensemble A **Figure 2**	t-shirt, cycle shorts, army socks, liner gloves, athletic shoes, over-boots, over-gloves, over-garment, respirator. CBA and webbing.	10.5 kg	standard undergarment dressing. over-garment - snug at ankles over the over-boots with strap ankle strap between sock and shoe layer. Snug at wrists over the over-gloves. Snug at waist with Velcro fastened on both sides of the body. All zips closed; zip fastened up under chin and Velcro zip cover closed. Hood closed snugly over lip of respirator. blue tack in holes of respirator. body armor and webbing snug fit over over-garment. no items in webbing.
Ensemble B **Figure 3**	t-shirt, cycle shorts, army socks, liner gloves, athletic shoes, over-boots, over-gloves, over-garment, respirator. CBA and webbing.	11.0 kg	standard undergarment dressing. over-garment - snug at ankles over the over-boots. Snug at wrists over the over gloves. Snug at waist (elastic strap in garment). All zips/ pockets closed. Zipped up from ankle to chin on both sides and Velcro zip covers closed. hood closed snugly over the lip of respirator. Blue tack in holes of respirator. body armor and webbing snug fit over over-garment. no items in webbing.
Ensemble C **Figure 4**	thermal long sleeve shirt, thermal long trousers, socks, athletic shoes, liner gloves, CB over-garment, over-gloves, over-boots, respirator, over-garment. CBA and webbing.	11.5 kg	Over-garment - snug at ankles over the over-boots. Snug at wrists over the over gloves. Snug at waist (elastic strap in garment). hood (of both intermediate and outer garment layers) closed snugly over the lip of respirator. Blue tack in holes of respirator. body armor and webbing snug fit over over-garment. no items in webbing.

Figure 2. Ensemble A

Figure 3. Ensemble B

Figure 4. Ensemble C

Human Research Volunteers – Study Design

Eight human research volunteers (age 23.9 ± 5.5 years; 178 ± 5.4 cm; 76.6 ± 8.4 kg; BMI 24.2 ± 2.7) participated in a controlled laboratory study. Volunteers conducted a 60 minute stage of exercise walking on a treadmill at 0.84 m/s (1.9 MPH) on level gradient (0 %), followed by a 10 minute rest period, and concluded with a second walking exercise period of 30 minutes at 1.68 m/s (3.8 MPH) at a inclined grade (3%). Each volunteer conducted this three stage testing wearing three different chemical protective ensembles (A, B, and C) for a total of 3 tests each and 72 time series periods (24 at level walking, 24 resting, and 24 increased speed at an incline). Volunteers were assessed within a controlled laboratory environment (air temperature (Ta): 29.3°C; relative humidity (RH) 56%; near still air ~0.4 m/s (indoors)) (Figure 5). Rectal temperature was collected throughout the duration of each study stage.

Figure 5. Human Research Study Design

Exercise Stage 1 (60 min) Treadmill Speed: 3 km/h Grade: 0%	**Rest** **(10 min)**	**Exercise Stage 2 (30 min)** Treadmill Speed: 6 km/h Grade: 3%
Laboratory Environment Air temperature: 29.3°C relative humidity: 56% Radiant temperature: indoor Wind-speed: still air		

Modeling and Analysis

A biophysics-based modeling approach was used to compare the predicted thermoregulatory responses to wearing each ensemble in given conditions [2]. Model inputs account for individual anthropometric data (e.g., height, weight), environmental inputs (ambient temperature (T_a, °C), relative humidity (RH, %), mean radiant temperature (T_{mr}, °C), and wind velocity (V, m/s)), activity rate (in watts), and inputs of the biophysical characteristics of the ensembles (thermal and evaporative resistances and calculations of wind velocity effects) [7].

The modeled human inputs assumed the average data measured from the human research volunteers: healthy male, normally hydrated, heat acclimated, 178 ± 5.4 cm; 76.6 ± 8.4 kg; BMI 24.2 ± 2.7). Modeled conditions for the environment, activity, and durations all mirrored the inputs from the human research exercise trials (Figure 5). Estimates of metabolic costs [8] were made for each volunteer specific to their own respective weights, each ensemble weight, and each activity (inputs shown in Table 3).

Table 3. Inputs for metabolic cost estimations

Element	Input Value
Weight	By subject (76.6 ± 8.4 kg)
Load	By clothing (10.5, 11, and 11 kg)
Speed	0, 3, and 6 km/h
Grade	0 and 3%
Terrain	Treadmill (value 1.0)

Root mean square deviation (RMSE) was used to compare the prediction outputs to the measured data. Using the RMSE equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

where d_i is the difference between observed and predicted T_c for each individual (°C), and n is the number of data points.

RESULTS

Biophysical Results

Table 4, shows all of the measured results for each ensemble and condition, for both laboratories. Figure 6 and 7 show graphically the thermal insulation (clo) and evaporative potential (i_m/clo) for each ensemble across the wind velocity test condition along with power regression lines between them to highlight the differences.

The measured biophysical data were predominantly in agreement between the two laboratories, with the exception of the R_{et} for ensemble C. According to the ASTM standards for R_t and R_{et} [3-4], reproducibility should be within 95% of the observed differences outlined in the standards. The 95% reproducibility in ASTM standards for R_t within labs is typically 0.009 °C·m^2/W and 0.024 °C·m^2/W between labs; while for R_{et} testing within labs should be 0.0025 kPa·m^2/W and 0.008 kPa·m^2/W. Each of the ensembles fell within this reproducibility limit for R_t (Figure 8); while ensemble C fell outside the reproducibility limit for R_{et} (Figure 9).

Table 4. Biophysical measures by wind velocity for each ensemble

Ensemble	Wind Velocity (m/s)	Thermal Resistance (R_t; m^2 K/W)	Thermal Insulation (clo)	Evaporative Resistance (R_{et}; m^2 Pa/W)	Permeability Index (i_m)	Evaporative Potential (i_m/clo)
A – US	0.40	0.29	1.86	64.97	0.27	0.14
A – AU	0.40	0.27	1.78	60.37	0.28	0.16
B – US	0.40	0.33	2.10	82.65	0.24	0.11
B – AU	0.41	0.32	2.08	78.97	0.25	0.12
C – US	0.40	0.38	2.45	149.03	0.15	0.06
C – AU	0.39	0.38	2.43	120.40	0.19	0.08
A – US	1.46	0.24	1.53	50.99	0.28	0.18
A – AU	1.13	0.23	1.45	45.67	0.30	0.21
B – US	1.45	0.27	1.74	63.36	0.26	0.15
B – AU	1.14	0.27	1.77	62.13	0.27	0.15
C – US	1.45	0.33	2.12	127.89	0.16	0.07
C – AU	1.12	0.33	2.10	106.47	0.19	0.09
A – US	2.29	0.21	1.35	41.16	0.31	0.23
A – AU	2.20	0.19	1.21	32.13	0.35	0.29
B – US	2.29	0.25	1.60	51.63	0.29	0.18
B – AU	2.18	0.24	1.53	45.67	0.32	0.21
C – US	2.27	0.31	1.98	114.08	0.16	0.08
C – AU	2.17	0.29	1.89	94.30	0.19	0.10

Figure 6. Total insulation (clo) by wind velocity each ensembles

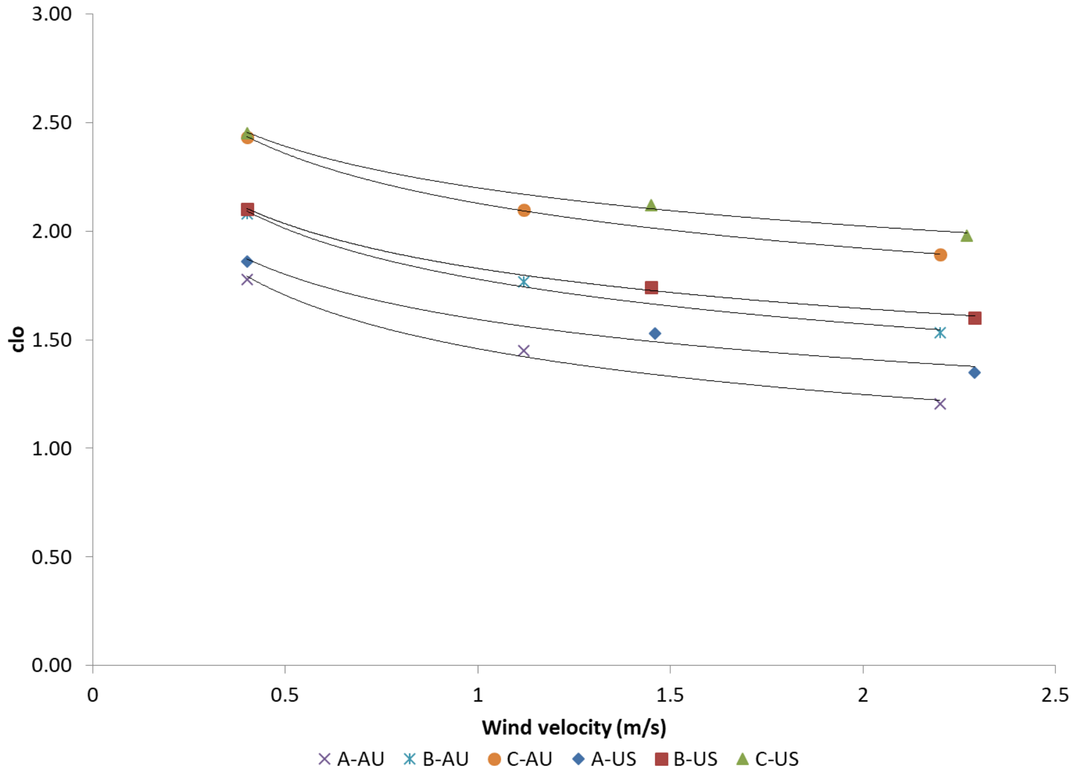


Figure 7. Evaporative potential (i_m/clo) by wind velocity for each ensemble

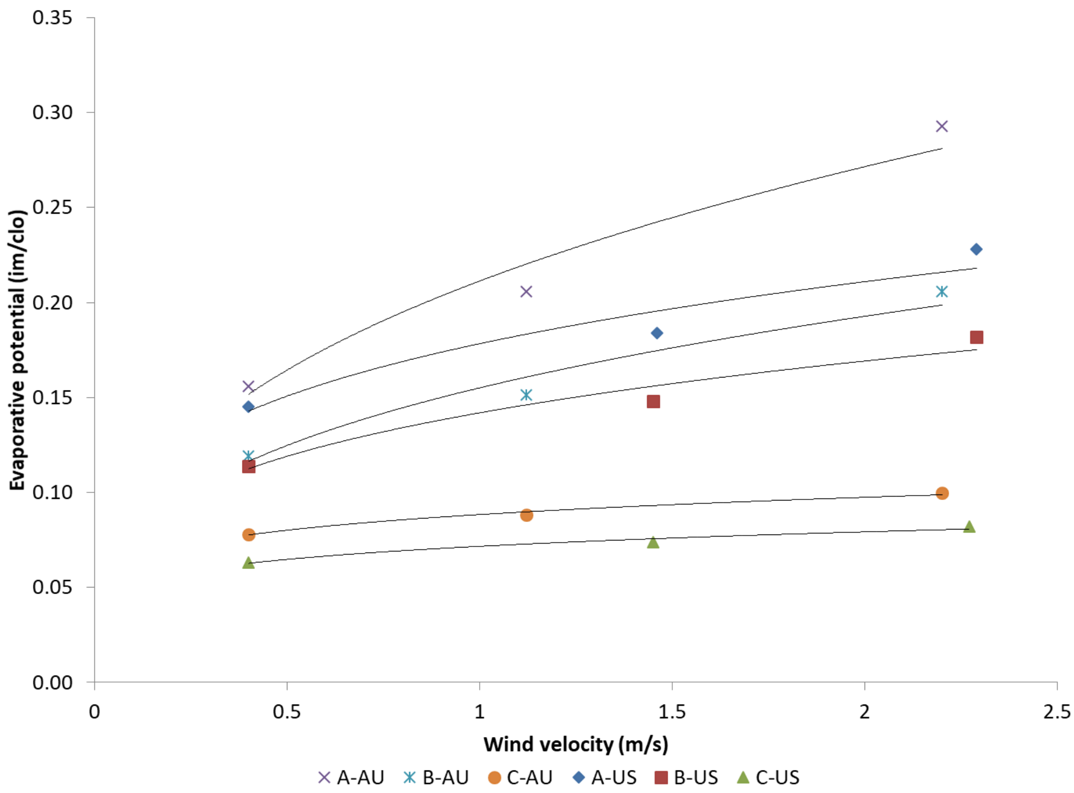


Figure 8. Differences in thermal insulation according to ASTM 95% reproducibility standard

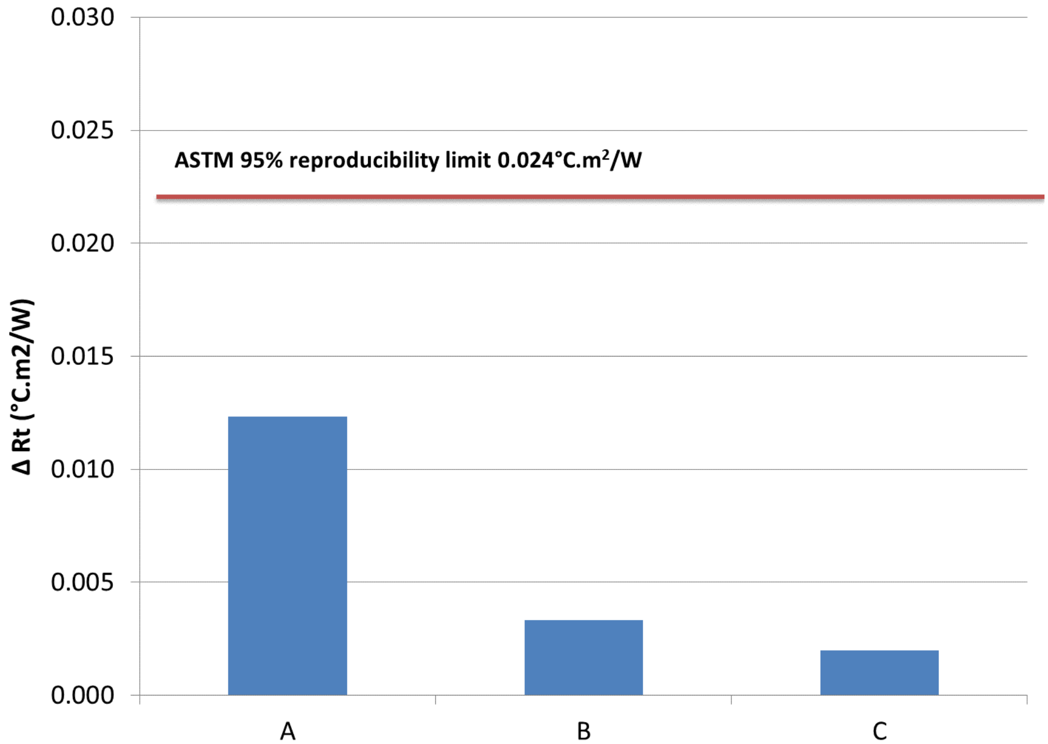
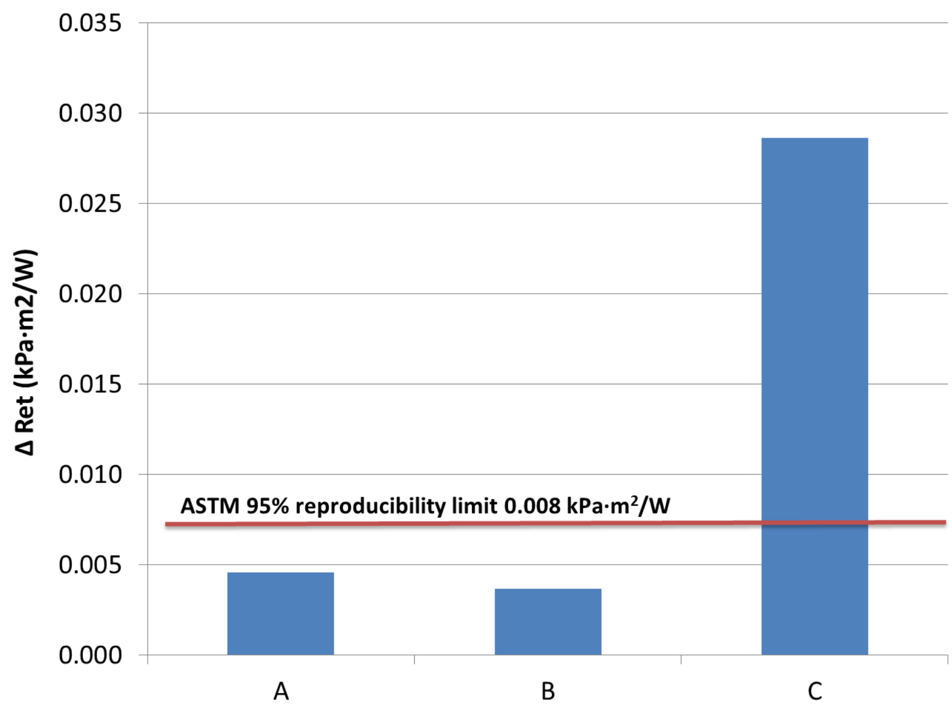


Figure 9. Differences in evaporative resistance according to ASTM 95% reproducibility standard



Human Research Data

All measures of rectal temperature (°C) are show in Figure 10. As can be seen in Figure 10, one set of data (Figure 10, Subject 1 A) was an obvious error in recorded data and was removed from the average values generated. A comparison of this data is shown in Figure 11.

Figure 10. Measured rectal core body temperature (°C) for all trials

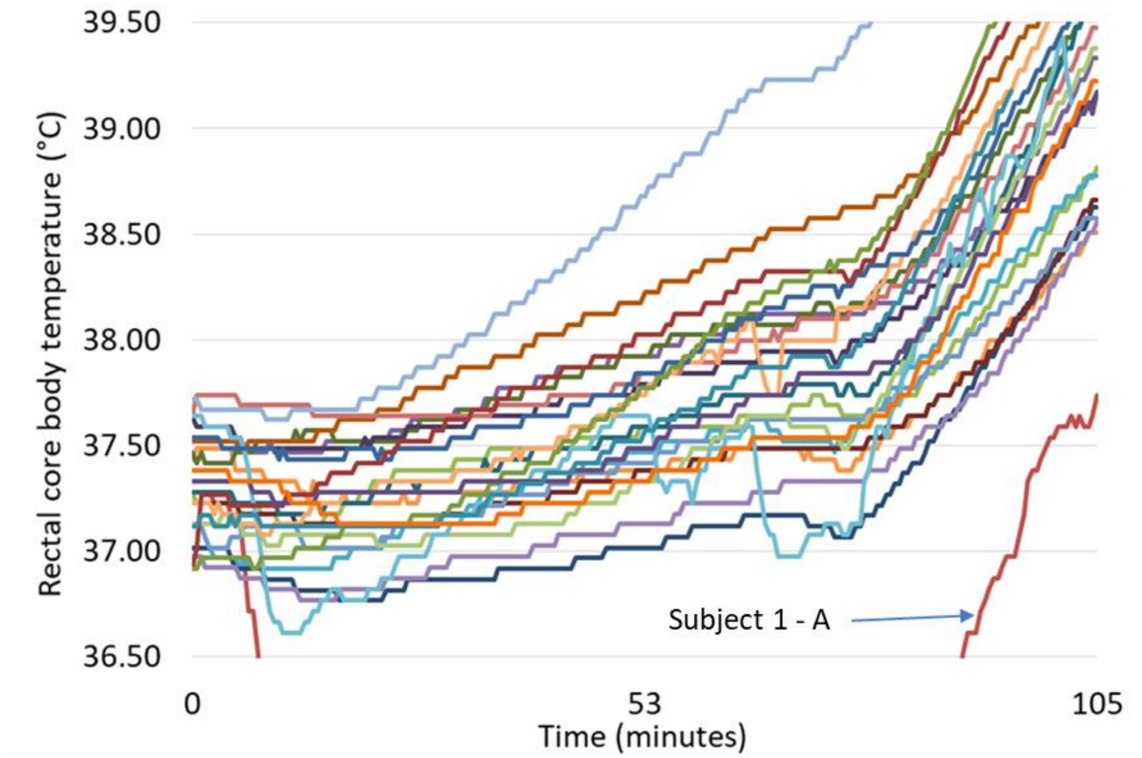
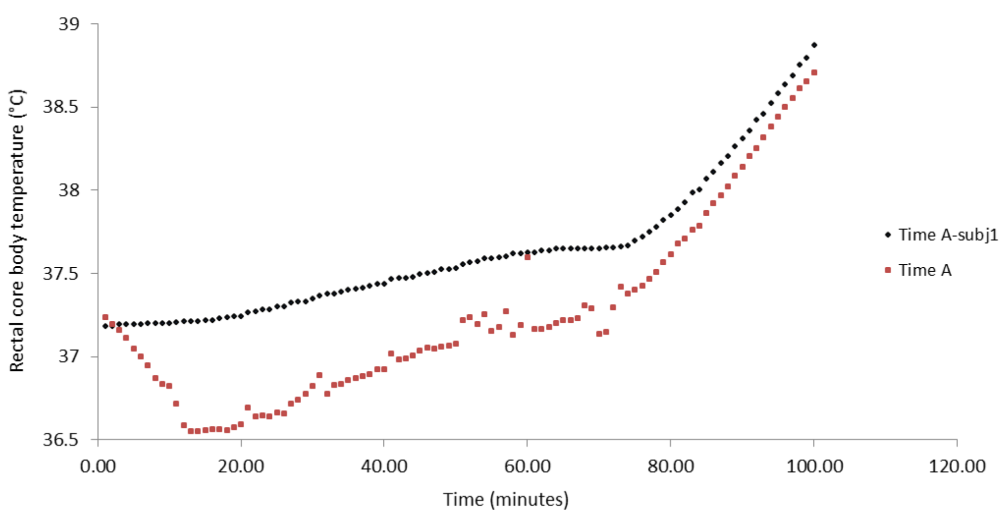
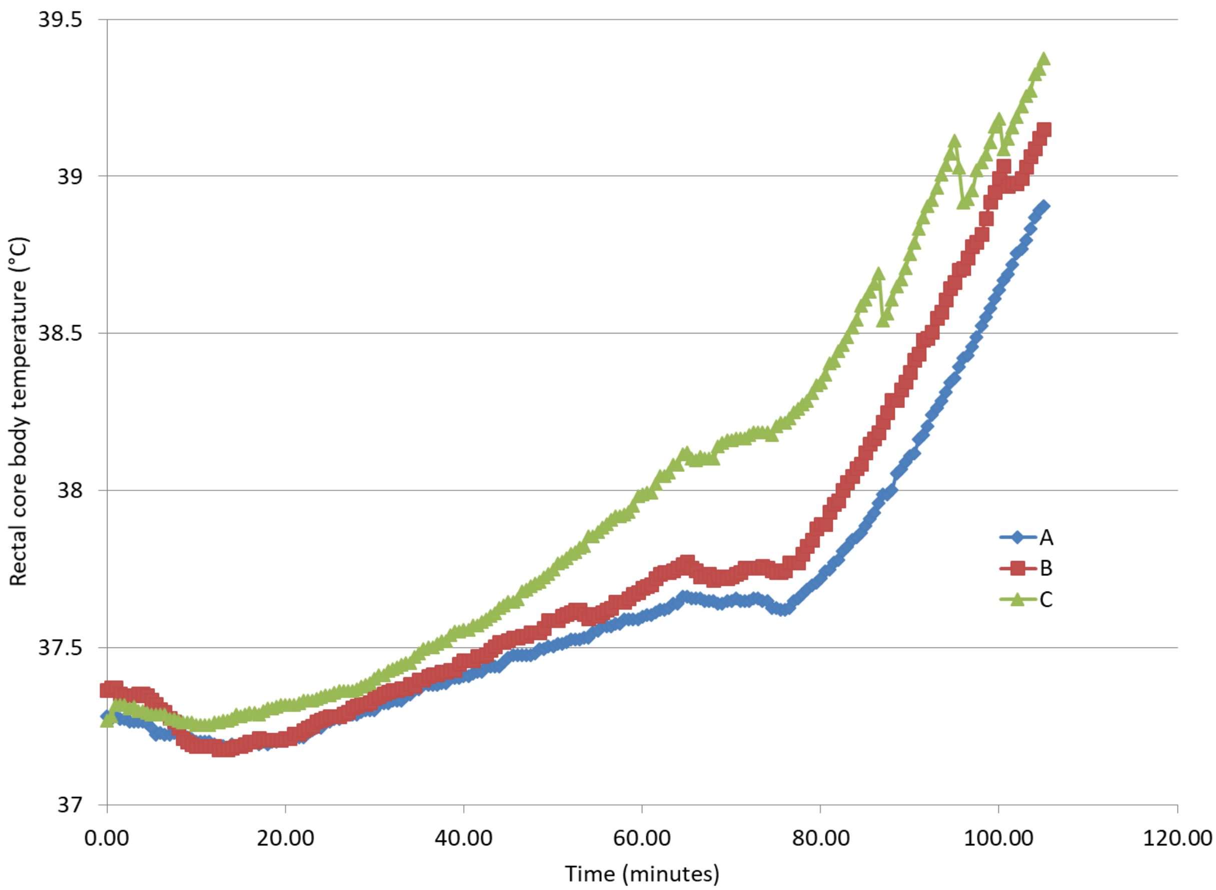


Figure 11. Comparison of average calculation for ensemble A data with (Time A) and without Subject 1 A (Time A-subj1)



The average values across all trials are shown in Figure 12 specifically by ensemble (with erroneous data removed). Several volunteers were unable to complete the full 30 min stage 2 work periods in the B and C ensembles, reflected in figure 12 by a sharp decline in the average rectal temperature trace.

Figure 12. Aggregate of measured rectal temperature across trials



Modeling Input values

Biophysical inputs

The modeling approach used requires four calculated or estimated biophysical inputs at 1 m/s wind velocity and exponent values (^{g}) for interpreting changes in wind velocity; specifically clo 1 m/s, a clo exponent (clo^g), i_m/clo 1 m/s, and an i_m/clo wind exponent (i_m/clo^g) (Table 5) [7].

Table 5. Calculated biophysics and wind velocity coefficients (^{g}) for 1.0 m/s

Ensemble	clo	clo^g	i_m/clo	i_m/clo^g
A – AU	1.46	-0.226	0.211	0.363
A – US	1.59	-0.176	0.178	0.243
B – AU	1.79	-0.183	0.155	0.310
B – US	1.83	-0.154	0.142	0.254
C – AU	2.13	-0.146	0.089	0.140
C – US	2.20	-0.120	0.072	0.146

Metabolic cost inputs

Estimations for modeling inputs of metabolic costs [8] are shown in Table 6. Given the minor difference between these values the modeled inputs were: Exercise Stage 1: 211 W; Rest: 114 W, and Exercise Stage 2: 490 W (43 W from external work (W_{ex}) against gravity).

Table 6. Estimated metabolic costs for each activity

Clothing	Exercise Stage 1	Rest	Exercise Stage 2
A	210 ± 21 W	114 ± 13 W	488 ± 48 W
B	211 ± 21 W	114 ± 13 W	491 ± 48 W
C	212 ± 21 W	114 ± 13 W	493 ± 48 W
Model Inputs	**211 W**	**114 W**	**490 W** (447 W + 43 W_{ex})

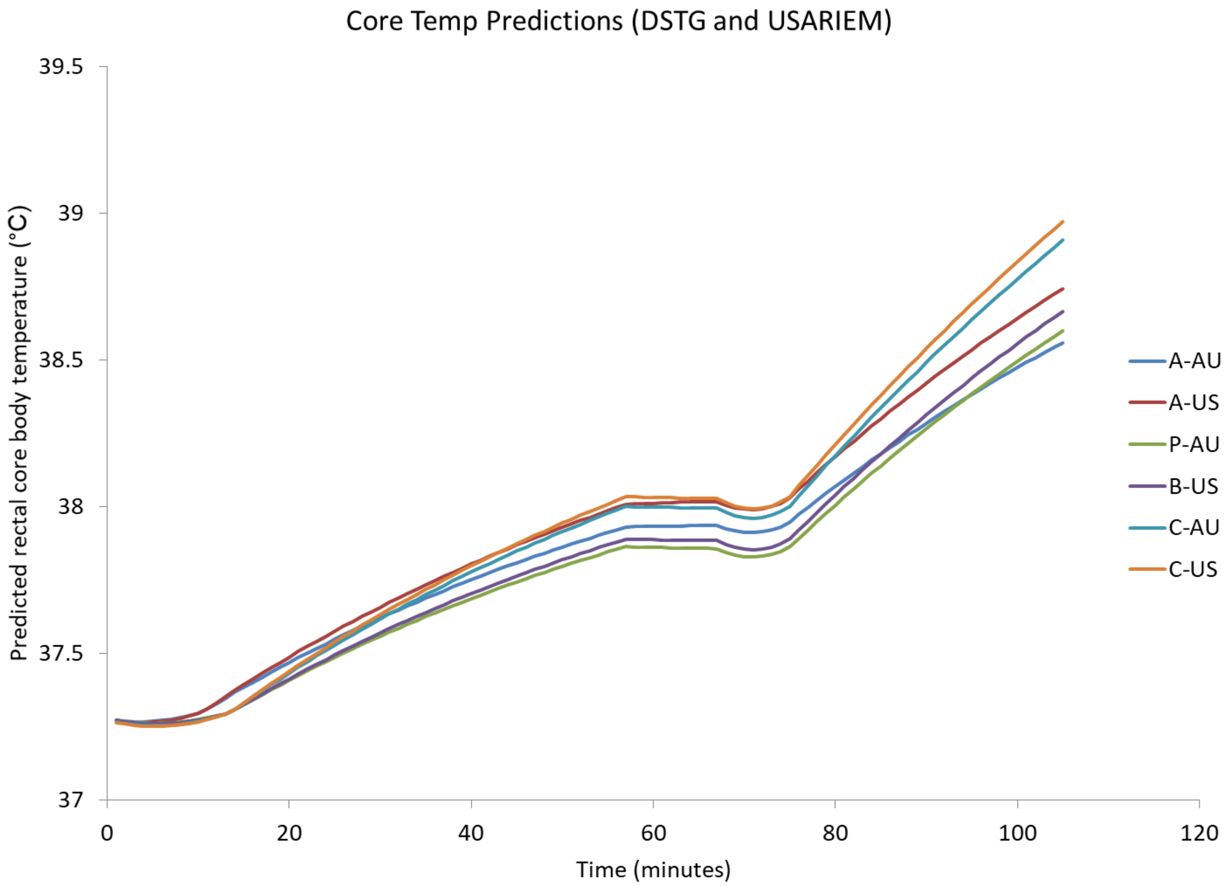
Modeling Results

Predicted rectal temperature based on manikin-obtained biophysical properties (Table 5) between the two laboratories are plotted in Figure 13. It can be observed that while differences in predictions are noticeable in biophysical data from the ensembles, they are likely negligible from a biophysical modelling perspective. Rectal temperature at the end of the work periods showed little difference between DST and USARIEM predictions for A, B, and C (Table 7).

Table 7. Predictions of core temperature and differences by end points for both DST (AU) and USARIEM (US)

	A-AU	A-US	B-AU	B-US	C-AU	C-US
End of Stage 1 exercise (60 minute mark)	37.93	38.01	37.86	37.89	38.00	38.03
Delta Δ	-0.08		-0.03		-0.03	
End of Rest Period (70 minute mark)	37.91	37.99	37.83	37.86	37.96	37.99
Delta Δ	-0.08		-0.03		-0.03	
End of Stage 2 exercise (100 minute mark)	38.56	38.74	38.60	38.67	38.91	38.97
Delta Δ	-0.18		-0.07		-0.06	

Figure 13. Predicted core body temperature from DST (AU) and USARIEM (US) data



For the purposes of model verification a comparison of the DST (AU) biophysical inputs was used and compared to the observed data and evaluated using RMSE. Figure 14 shows the overall comparison of model predictions and observed data; while Figures 15-17 show specific ensemble comparisons. The calculated RMSE was relatively low for each ensemble; 0.70°C for A, 0.37°C for B, and 0.25°C for C. Figures 15-17 show graphically the comparison of each prediction to each observed set, with point-by-point standard deviations shown as error bars for each. Similar to work done by Cadarette et al., [9], using a threshold of two times the standard deviation provides an indication that the predictions fall within 95% of an average population's response. Figures 18-20, show the comparison of the predicted and observed results along with error bars representing the standard deviations times two for reference. These figures show that the model predictions were all within this 2*SD limit, indicating an acceptable level of reliability.

Figure 14. Overall comparison of model predictions and observed data

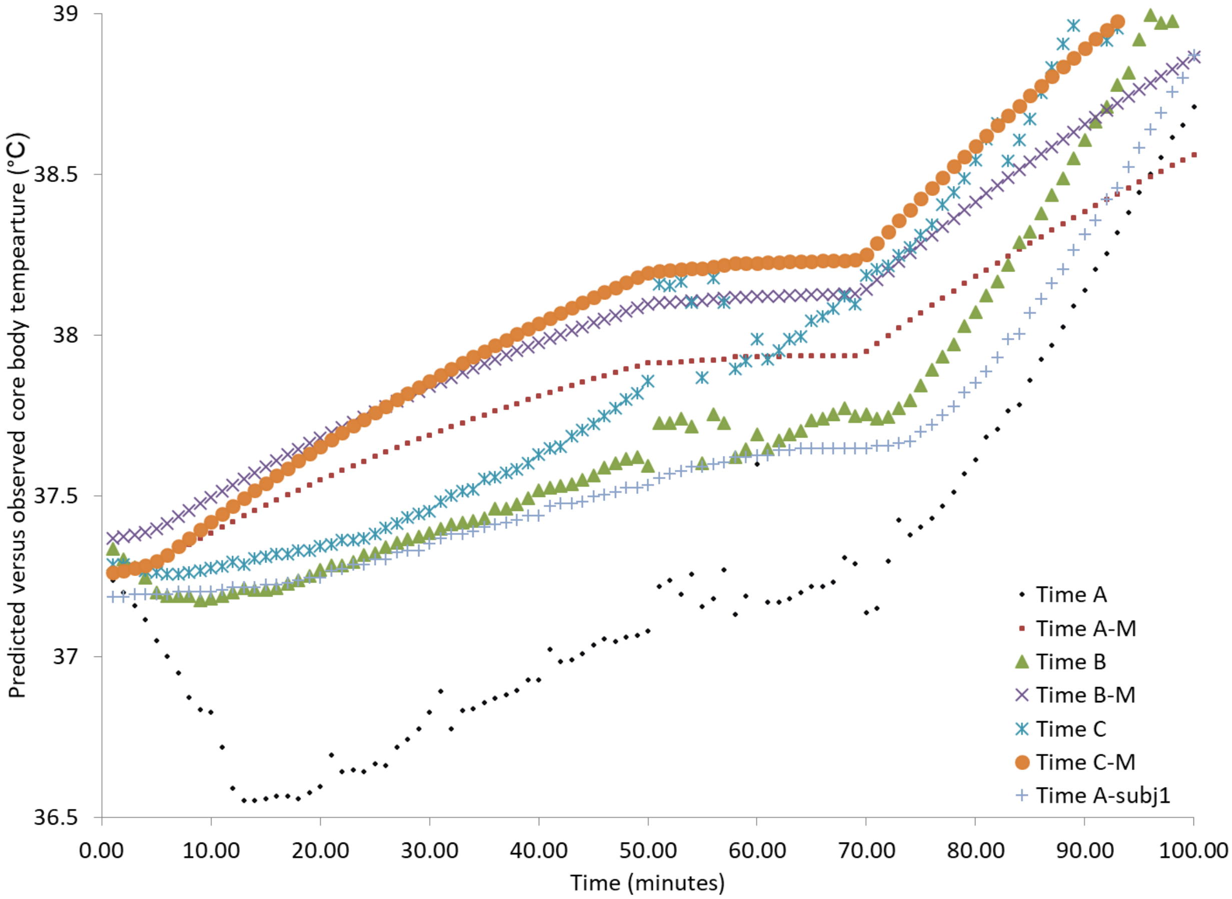
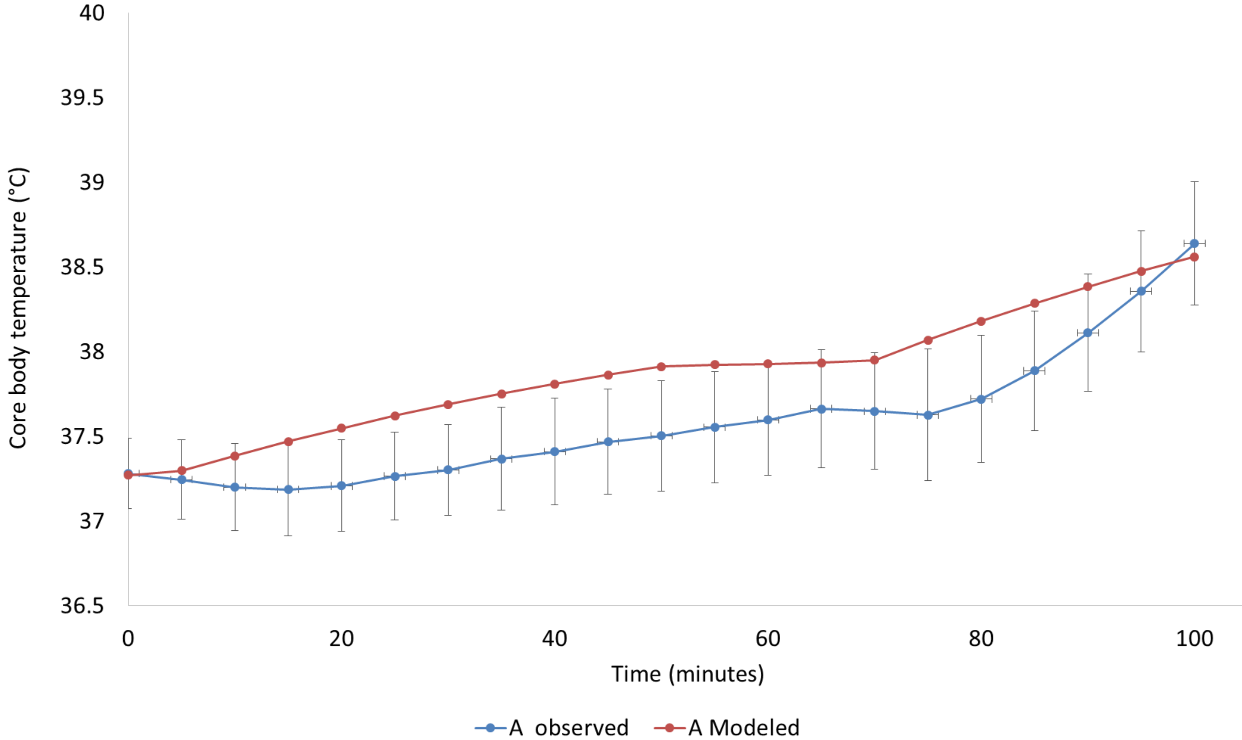
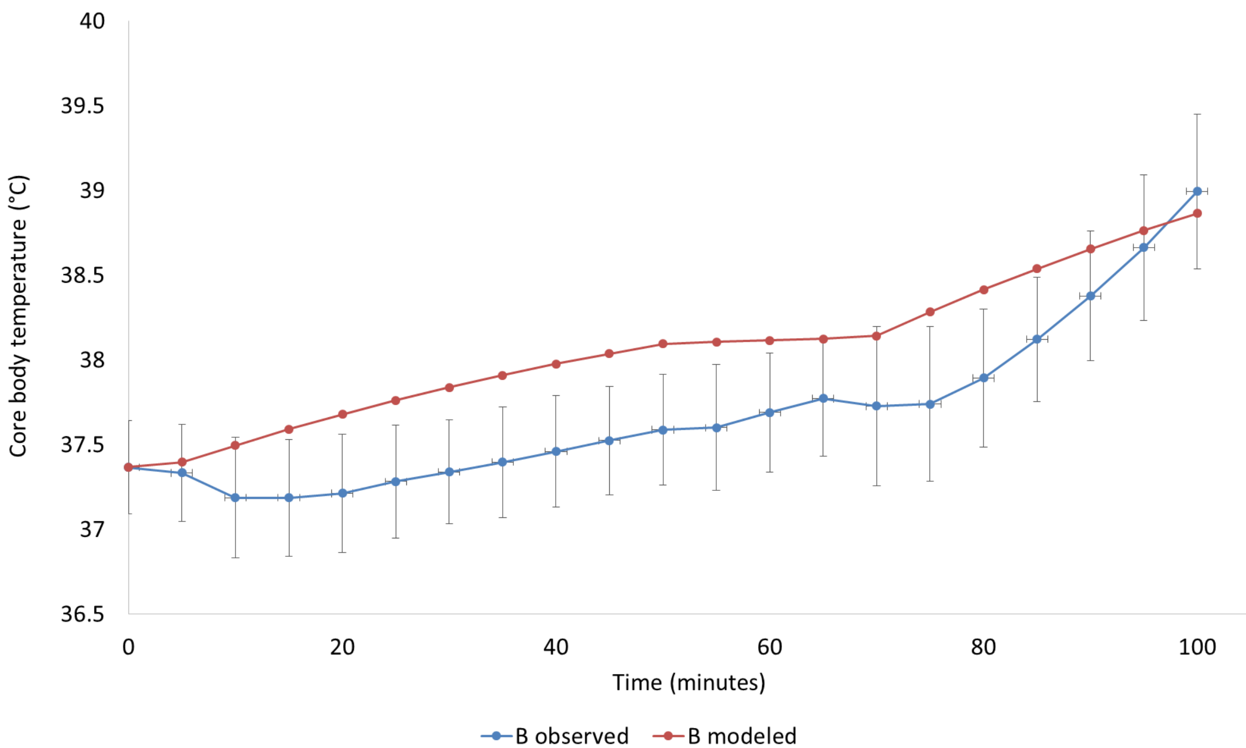


Figure 15. Comparison of observed and modeled for ensemble A



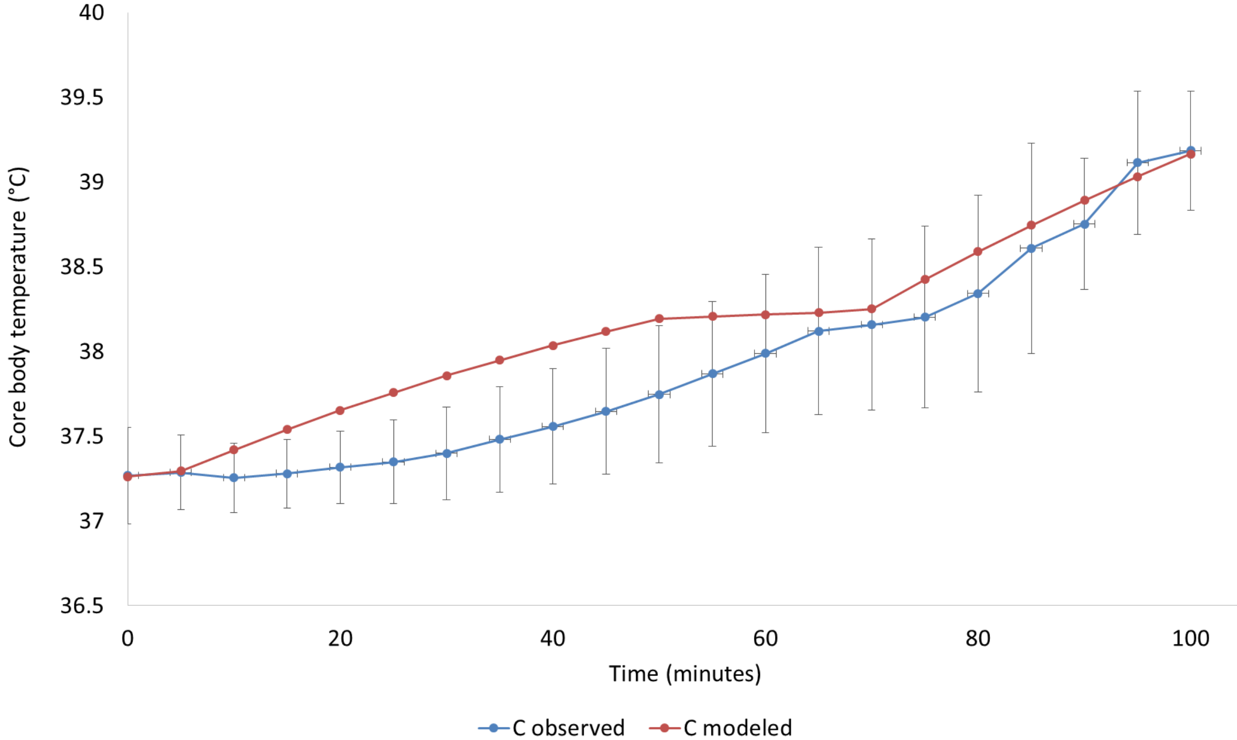
*error bars show observed standard deviation

Figure 16. Comparison of observed and modeled for ensemble B



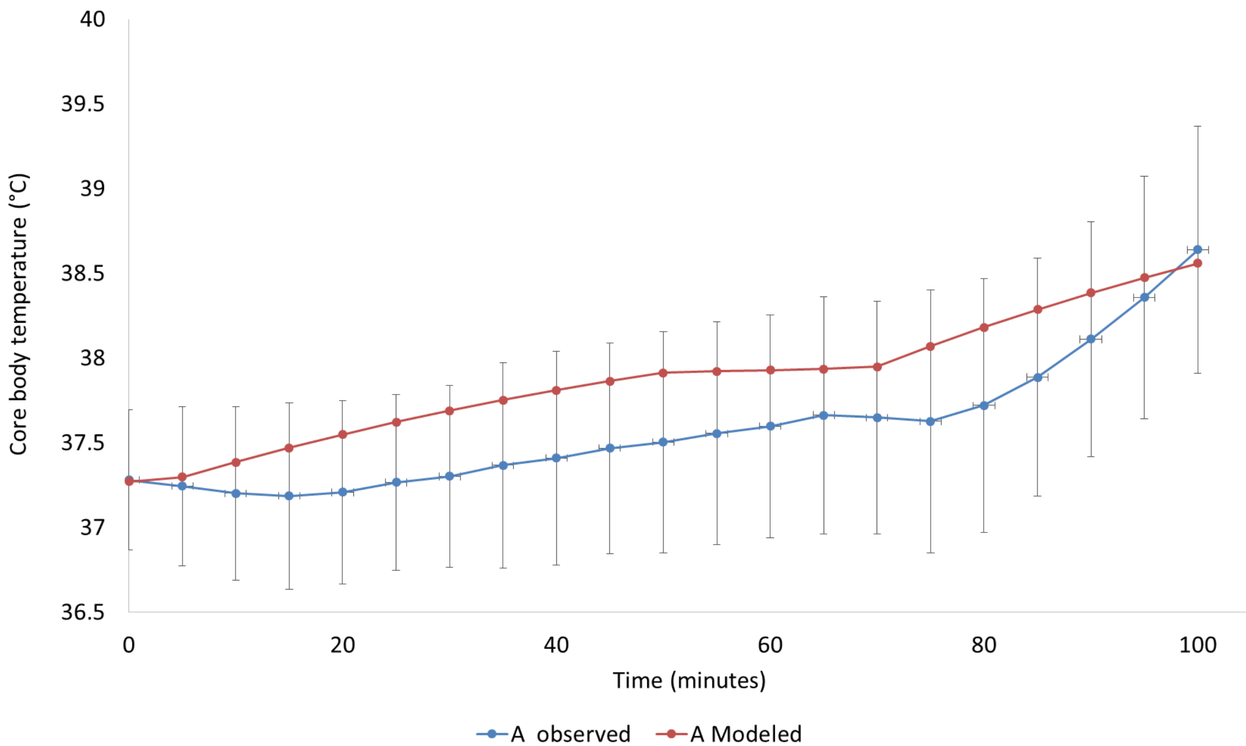
*error bars show observed standard deviation

Figure 17. Comparison of observed and modeled for ensemble C



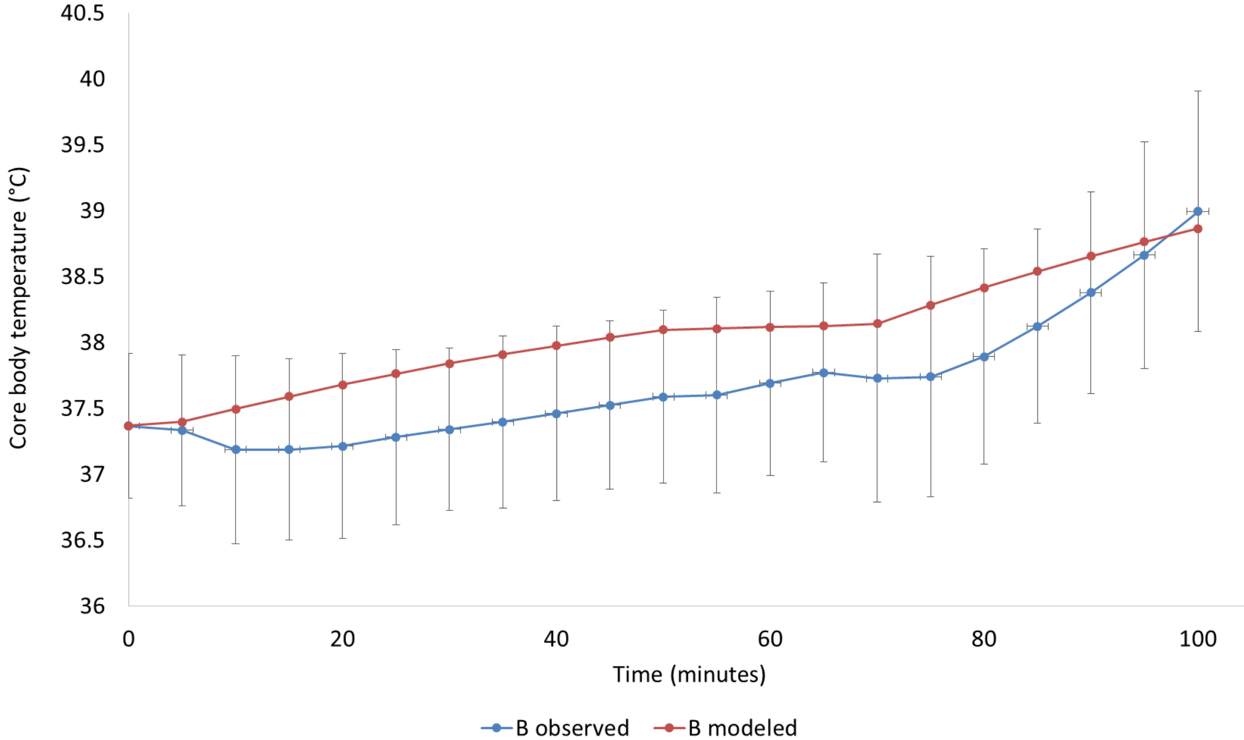
*error bars show observed standard deviation

Figure 18. Observed and modeled for ensemble A compared to 2*SD



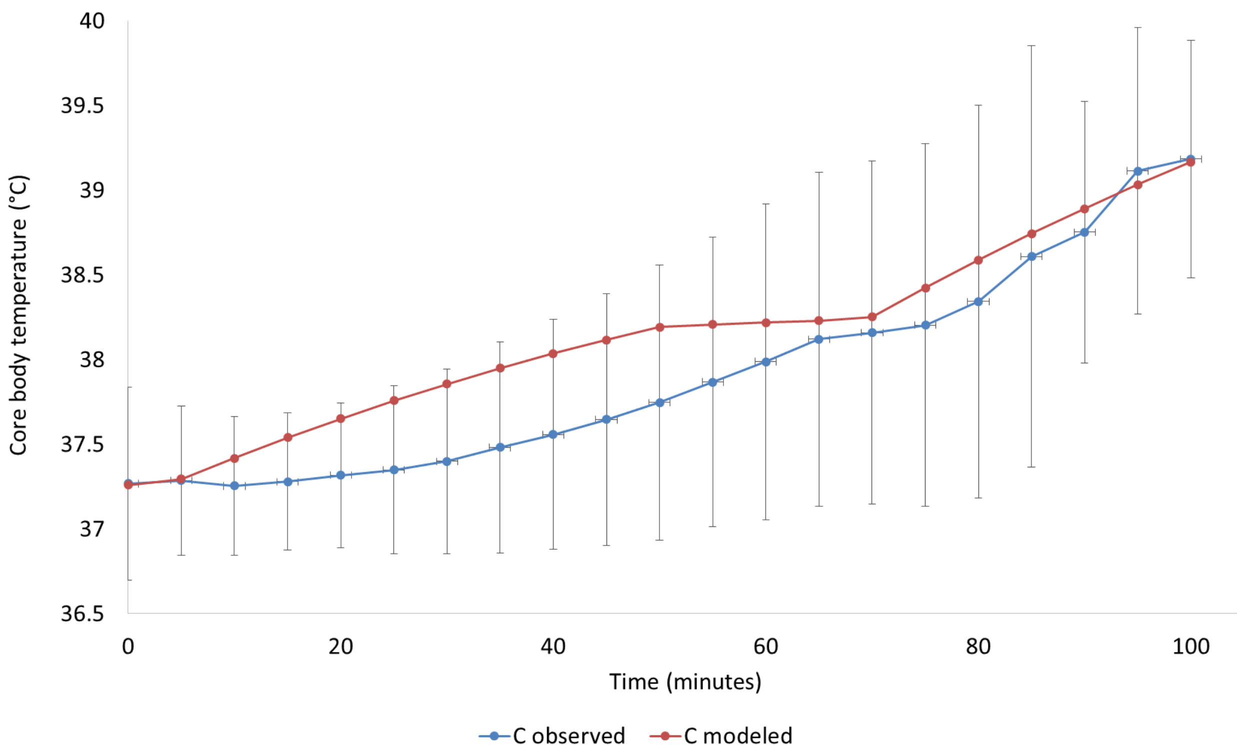
*error bars show observed standard deviation times two (SD*2)

Figure 19. Observed and modeled for ensemble B compared to compared to 2*SD



*error bars show observed standard deviation times two (SD*2)

Figure 20. Observed and modeled for ensemble C compared to compared to 2*SD



*error bars show observed standard deviation times two (SD*2)

DISCUSSION

The study has revealed good agreement between the USARIEM and DST laboratories on biophysical data measurements, specifically for the thermal insulation of all ensembles evaluated in the present study, and all but the most burdensome ensemble for the evaporative resistance (ensemble C). Agreement was confirmed by meeting the ASTM reproducibility criteria for thermal insulation and evaporative resistance, for tests conducted at 0.4 m/s wind velocity. An important finding however, was that the effects of wind-velocity appears to be exaggerated at the DST laboratory, with thermal insulation and evaporative resistance changing to a greater degree for a given increase in wind velocity.

Chambers and wind tunnels are designed to reduce turbulence within the measured environment; however, given the dynamic nature of air flow and varied designs of these chambers, it is likely a reason for some of the measured disparities between interlaboratory testing. A potential issue with measured variance between laboratories and manikin operations [10, 11] is wind turbulence as a result of chamber size and shape differences [12]. Having a chamber wind velocity set point of 0.4 ms^{-1} causes the fans to oscillate in order to compensate in an attempt to maintain a constant value. While these oscillations may be minor, it likely causes less stability within the chamber environment and therefore more variance in measures, i.e., less than optimal steady-state conditions. Rather than having a set point for the chamber wind velocity conditions, a constant power setting of the fans, as used in this study, may be a more optimal method for measurements.

In spite of the different effects of wind velocity on the biophysical measurements of the clothing ensembles, there were minimal differences in the biophysical modeling estimates of physiological strain. Both USARIEM and DST ensemble data provided estimates of rectal temperature that differed on average by only 0.07°C across the given work scenarios. Therefore, biophysical modelling can be readily compared between the laboratories. This finding provides confidence in the consistency of advice provided to operational and training personnel on risk management for work in the heat between the two laboratories when utilizing the HSDA model.

Furthermore, this study has shown the agreement between the HSDA predictions of rectal temperature response to a work scenario with the physiological strain experienced by human participants. The model was originally designed using a large sample population of data and made conservative predictions to account for the average core body temperature within the population. While the conservative nature of the original version of the HSDA model would ultimately protect the larger population, it would likely over predict rise in core body temperatures for the fit or more experienced individuals. While modular improvements to the model have been implemented over time (e.g., altitude, heat acclimatization), more work is needed to add factors for population-based differences (e.g., fitness, body composition).

CONCLUSIONS

This study clearly outlines a beneficial collaborative relationship between two laboratories with similar interests. From the data provided above there are not only scientific findings of merit but functional improvements that can begin to be made to some of the evaluation methods used within this scientific field. While differences were observed in the collected data of the manikins and the predicted values for human physiological outcomes; overall this work proves reproducibility and value in the combined use of these evaluation methods.

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